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Several important questions related to cavity expansion and pressuremeter testing in clays are being investigated. Tests are performed in a cuboidal shear device to simulate pressuremeter stress paths and to evaluate the strain rate effects. Similarly, experiments will be conducted to evaluate effects of stress relief, relaxation and disturbance. Model pressuremeter tests will be performed in a calibration chamber to confirm the strain rate effects obtained in the cubic triaxial simulation and verify the applicability of the interpretation technique based on anisotropic model to determine the initial in-situ stress. The calibration chamber test equipment is currently being redesigned and modified to perform the model pressuremeter tests. The experimental data will be used to calibrate the anisotropic soil model developed for this study. With this model, one can predict the behavior of clay type material under any desired stress path from the results obtained under a particular stress path, such as the pressuremeter stress path.

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ANNUAL TECHNICAL REPORT

ANISOTROPIC BEHAVIOR OF SOILS AND PRESSUREMETER TESTS

SUMMARY:

Several important questions related to cavity expansion and pressuremeter testing in clays are being investigated. Tests are performed in a cuboidal shear device to simulate pressuremeter stress paths and to evaluate the strain rate effects. Similarly, experiments will be conducted to evaluate effects of stress relief, relaxation and disturbance. Model pressuremeter tests will be performed in a calibration chamber to confirm the strain rate effects obtained in the cubic triaxial simulation and verify the applicability of the interpretation technique based on anisotropic model to determine the initial in-situ stress. The calibration chamber test equipment is currently being redesigned and modified to perform the model pressuremeter tests. The experimental data will be used to calibrate the anisotropic soil model developed for this study. With this model, one can predict the behavior of clay type material under any desired stress path from the results obtained under a particular stress path, such as the pressuremeter stress path.

STATUS OF THE RESEARCH

The original proposal outlined research to be carried out over a period of two years. This report summarizes the results and accomplishments made during the period August 1989 to June 1990. Although the principal investigator and two graduate students,

Messrs. Skandarajah and Penumadu, participate in all aspects of the research, the three sections that follow correspond to the three different areas of work where each one of them was most active.

Strain rate effects and pressuremeter testing in the cuboidal shear device (A. Skandarajah).

Several aspects of the research relate to the simulation of cavity expansion stress paths in the cuboidal shear device, and the evaluation of strain rate effects:

- The existing software was modified to simulate the strain path of a pressuremeter test in the cuboidal shear device.
- More than 25 tests were performed on reconstituted kaolin clay (LL = 63, PI = 27) with various strain rates ranging from 0.01%/min to 5.0%/min.
- Due to difficulties in obtaining natural soils, a second soil (LL = 37, PI = 15), synthesized by mixing equal portion of kaolin clay and very finely ground silica, was also used in the strain rate experiments. Seven tests have been conducted on this material to date, and additional tests will be performed during the second year of the research program.
- The software has been recently modified to run stress relaxation tests. Three tests have already been performed using this program. Several more relaxation tests will be carried out in the coming months.

A summary of the strain rate tests are shown in Figure 1 for

the kaolin clay and in Figure 2 for the kaolin-silica mixture. All the shear strength values are normalized using 0.01%/min as the reference strain rate in order to compare with previously published data. The normalized shear strength increases linearly with the logarithm of strain rate, the increase being of the order of 15% to 18% by order of magnitude of strain rate.

The pressuremeter stress path-strain rate test results obtained in the cubic triaxial device are superimposed with triaxial test results obtained by Bjerrum (1972), Vaid and Campanella (1977) and Nakase and Kamei (1986) in Figure 3. Prapaharan (1987) combined all the existing strain rate test data for the triaxial mode, and proposed a bi-linear relationship also shown in the figure, with an increase in shear strength of only 10% for every log cycle of strain rate. The cuboidal shear device test results for pressuremeter stress path indicate that the increase can be larger, of the order of 15% for the kaolin soil and 18% for the kaolin-silica mixture. It is noted that the Nakase and Kamei's results also suggested that the gradient was soil dependent.

To compare the effects of different strain rates on the shear strength, typical tests for each strain rate are plotted in Figures 4 and 5 for kaolin and kaolin-silica mixture, respectively. All the stress-strain curves for kaolin clay exhibited strain softening behavior. According to Jamiolkowski and Lancellotta (1977) higher strain rates produce stress-strain curves with excessive strain softening and a pronounced peak. The test results agreed with some of the above mentioned features. However, the stress-strain curves for kaolin-silica mixture showed strain hardening.

As Nakase and Kamei (1986) noticed in their K_o-consolidated triaxial tests on cohesive soils at different strain rates, the tests reported herein also show that the maximum principal stress difference and the strain at failure increase with strain rate, and the pore pressure coefficient at failure, A_f, decreases. Furthermore, the tests show that the undrained shear strength and initial tangent modulus increase with strain rate, consistent with other researchers' results (e.g. Casagrande and Wilson, 1951; Crawford, 1959; and Richardson and Whitman, 1963).

In the second year of the research, the following tasks will be continued or undertaken:

- Complete the strain rate effect tests on the second soil (kaolin-silica).
- Conduct the stress relief and relaxation tests.
- Develop an analytical technique to estimate the rate effects for stress paths in SBPM tests. Incorporate rate effects into the anisotropic constitutive model (Thevanayagam et al., 1988).
- Assess the influence of strain rates on the stress relaxation test results.
- Study the effect of using a slightly larger pressuremeter than the borehole diameter on the derived undrained shear strength using the cuboidal shear device.

Modelling Anisotropy at Critical State (J. L. Chameau and S. Thevanayagam)

The work undertaken by Thevanayagam (1988) was continued, leading to the writing of a technical paper (a copy of this paper has already been submitted to AFOSR). In this paper, recent

developments related to Cam Clay models are summarized, and a different approach to interpret these developments in terms of physical parameters of clays is presented. A new state variable, ψ, indicative of the fabric of clays is introduced. Based on these concepts and a general failure criterion, a simple model to predict failure parameters of anisotropic clays for many commonly encountered stress paths is developed. The model capability to interpret in situ strength measured under a given stress path and transfer it to another stress path is illustrated. Finally, the ability to obtain failure parameters for any stress path using data from a single CIUC test is demonstrated.

The general concept of this approach and its advantages are summarized as follows (conclusions of paper by Thevanayagam and Chameau):

- The work assumptions of the Cam Clay, Modified Cam Clay, and Anisotropic Cam Clay models have been illustrated using a general dilatancy relationship. The basis of these models can be related to a first order soil structure state variable, ψ. This presents a different approach to modeling of soil behavior from the standpoint of fabric, and offers the possibility of introducing soil fabric into constitutive models.
- A general form of the failure surface f^f introduced with the anisotropic cam clay model in triaxial space allows for the determination of failure parameters for any mode of failure.
- The notion that mean stress at failure is dependent on the mode of undrained failure is included in the model,

and the initial anisotropy is properly taken into account in the yield surface and failure criteria.

- The effect of induced anisotropy is captured and incorporated by a calibration procedure. Given the initial conditions of the soil, the complete failure behavior at critical state (strength, pore pressures, friction angles, etc.) for many selected modes of failure can be predicted. Failure parameters obtained from one mode of failure can be converted to another stress path applicable to a given design problem.
- The relationships derived in this work can be related using the two commonly used soil parameters, ϕ_c and OCR. It has also been illustrated how the data obtained from a conventional CIUC test could be used to obtain failure parameters of K_0 consolidated natural clays for any mode of failure.

This work will be continued further next year, with emphasis on the writing of a paper describing the application of these concepts to the pressuremeter. As indicated in the previous section, the inclusion of stress rate effects will also be attempted.

Intermediate principal stress effects and cavity expansion simulation (D. Penumadu).

During the first four months of his work on this project, Mr. Penumadu, being new to the research program, devoted his time to reviewing the relevant literature, including several recent dissertations. Then he took a more active part in the research as

outlined in the following.

Using the results of the cuboidal shear device tests on K_o consolidated kaolin clay under essentially plane strain conditions (CK_oUC), the variation of intermediate principal stress during shear was studied. A spreadsheet based program was developed to automate the data reduction. The measured variations of the stress ratio b = $[\sigma'_2/(\sigma'_1 + \sigma'_3)]$ with respect to strain were found highly repeatable and the changes in these coefficients are different from predictions made with the Cornforth and Bishop models (Cornforth, 1964 and Bishop, 1966). For several tests already analyzed, the initial values of the b ratio range between 0.35 and 0.39, comparable to the expected value of 0.39 for the kaolin clay used in the study. However, the b value at large strains ranges between 0.65 to 0.85, which is significantly larger than the values (0.40 to 0.50) predicted by the Cornforth (1964) and Bishop (1966) models. The amplitude and physical importance of the intermediate principal stress is still a topic of debate, and these preliminary results show that further evaluation is necessary. Hence, this aspect of the research will be continued, as well as a study of the variation of stress invariants with respect to strain. The stress invariant approach obviates the fact that stress invariance is valid at a point of soil sample and not for the soil sample as a whole.

A computer program was written in quick basic for multi-order polynomial regression of pressuremeter expansion curve data to obtain the stress-strain relationship (Fyffe et al., 1986). These results will be compared to the interpretation technique using

simplex curve fitting algorithm (Huang, 1986). This study will help clarify the effects of the type of interpolation technique on the derived stress-strain curves.

Several changes are being made to the existing calibration chamber system. All the pressure regulators and several plumbing lines of the equipment were replaced or modified. To assure a rigid system in the horizontal direction, internal and external cell pressures are to be kept the same throughout the K_o consolidation and probe expansion phase. In earlier work, this was done manually, and thus imperfect. A new control system was designed to alleviate this problem. A differential pressure transducer will monitor the internal and external cell pressures and an electric to pneumatic pressure regulator will be used to maintain the same pressures throughout the testing phase. The data acquisition and control system used in the earlier research (Maxim 2) is outdated and no longer in service. Hence a new Keithley series 500 with IBINA interface card installed on an IBM PC as the hardware interface will be used for data acquisition. SOFT 500 software was selected for acquisition and control. Another problem faced in earlier research (Huang 1986) was the imperfect response of piezometers. In the modified system, a new design is incorporated for end platens to yield better pore pressure measurements. Finally, a new slurry mixing tank is developed which will allow for the preparation of kaolin under vacuum using standard chemical mixers, and the associated slurry consolidometer is under the design phase.

All modifications to the testing equipment will be completed by the end of the summer of 1990; they will be followed by a series

of experiments designed to support the theoretical and conceptual aspects of the research. Hence, the tasks on which Mr. Penumadu will concentrate can be summarized as follows:

- Variation of Intermediate Principal Stress - Complete the study on the variation of intermediate principal stress and provide guidelines on how to best approximate it.
- Physical aspects of calibration chamber testing procedure - Incorporate the differential pressure transducer, electric to pneumatic transducer, and the modified end platens in the calibration chamber. Computer hardware modifications include setting up and configuring analog input multiplexers, A/D converter and digital output boards. The software for automatic data acquisition, storage and reduction using SOFT 500 will be completed.
- Laboratory testing of model pressuremeter - Strain controlled model pressuremeter testing will be performed on K_o consolidated kaolin clay using different strain rates. The concept of increase in shear modulus with strain rate will be verified using the above test results. The use of stepper motor control DAS boards will allow for an infinite combination of strain rates.

- Determination of initial insitu stress and position of the cavity wall - Artificial disturbance will be created by understressing the cavity. The results of these tests with disturbance will be complemented by ideal pressuremeter tests. The data obtained will be used to check the analytical method that has been proposed

(Thevanayagam, Skandarajah and Chameau, 1988) to determine the initial undisturbed state of the cavity wall. This data will also be useful to evaluate the effect of type of disturbance on stress-strain curves.

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LIST OF PUBLICATIONS

The following publications acknowledge support of the U.S. AFSOR related to pressuremeter testing and cavity expansion in clays.

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Thevanayagam, S., Altschaeffl, A. G. and Chameau, J. L., "Cam-Clay Based Anisotropic Model for Pressuremeter Tests", ASCE Engineering Mechanics Division Specialty Conference, San Diego, July 1989.

Thevanayagam, S. and Chameau, J. L., "Modelling Anisotropy of Clays at Critical State", submitted for publication in ASCE, 1990.

PERSONNEL

Principal Investigator: J. L. Chameau

Graduate Research Assistants: D. Penumadu and A. Skandarajah

INTERACTIONS

Close contacts were kept with individuals involved in earlier aspects of this research, such as Prof. Huang (Clarkson U.), and Dr. Thevanayagam (Earth Technology). Dr. Huang provided assistance in the design of modifications to the calibration chamber. Results of the work performed at Purdue University were presented at the last ASCE-Engineering Mechanics Specialty Conference in San Diego (July 1989), and at the International Symposium on Pressuremeters in London (March 1990). It is also noted that many researchers from other U.S. and foreign universities visiting the Purdue geotechnical laboratories were demonstrated the use of the equipment developed for this study (calibration chamber, cuboidal shear device, and model pressuremeter).

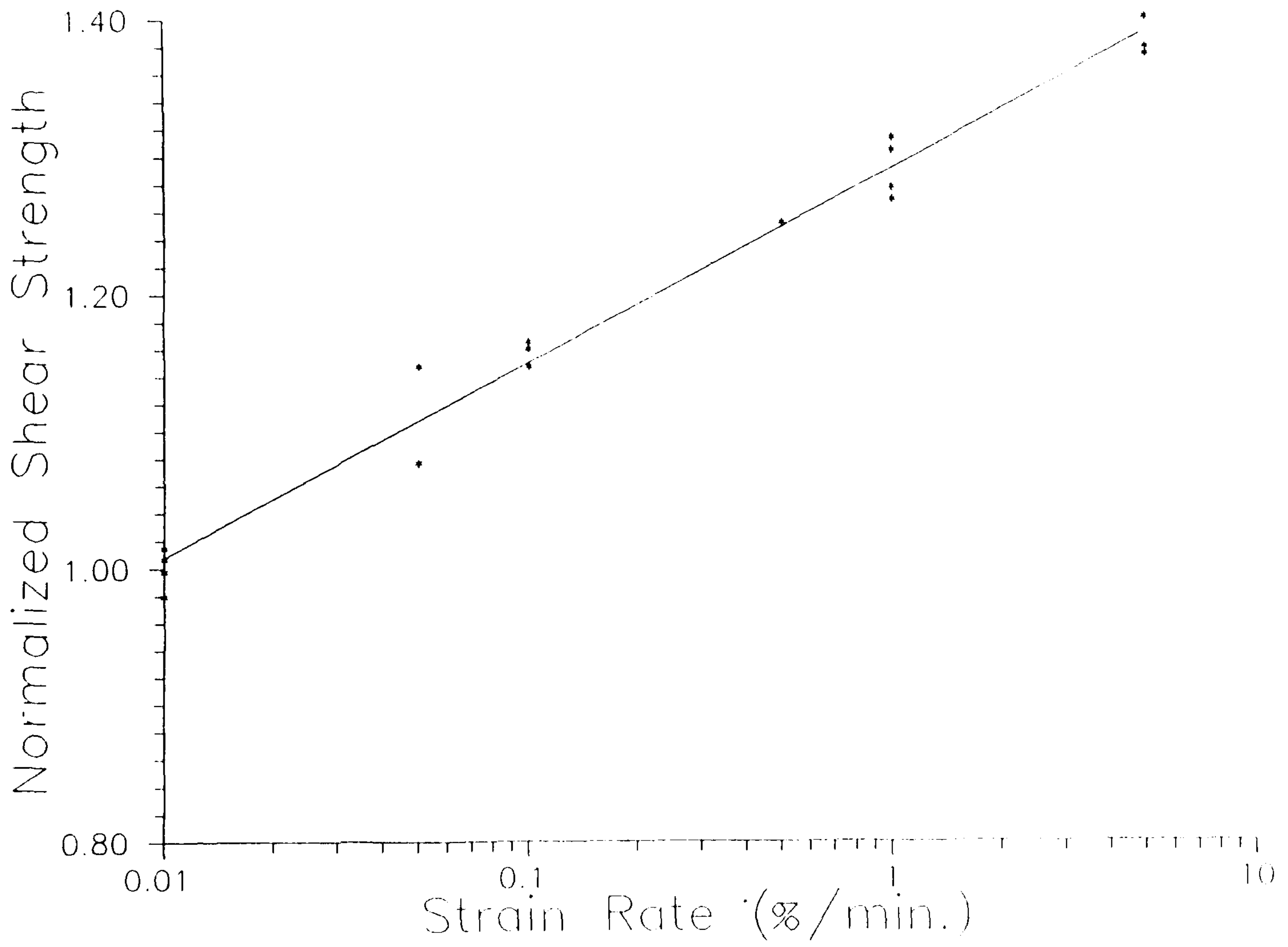

FIG. 1: NORMALIZED SHEAR STRENGTH W.R.T. 0.01%/MIN. VS STRAIN RATE FOR KAOLIN CLAY

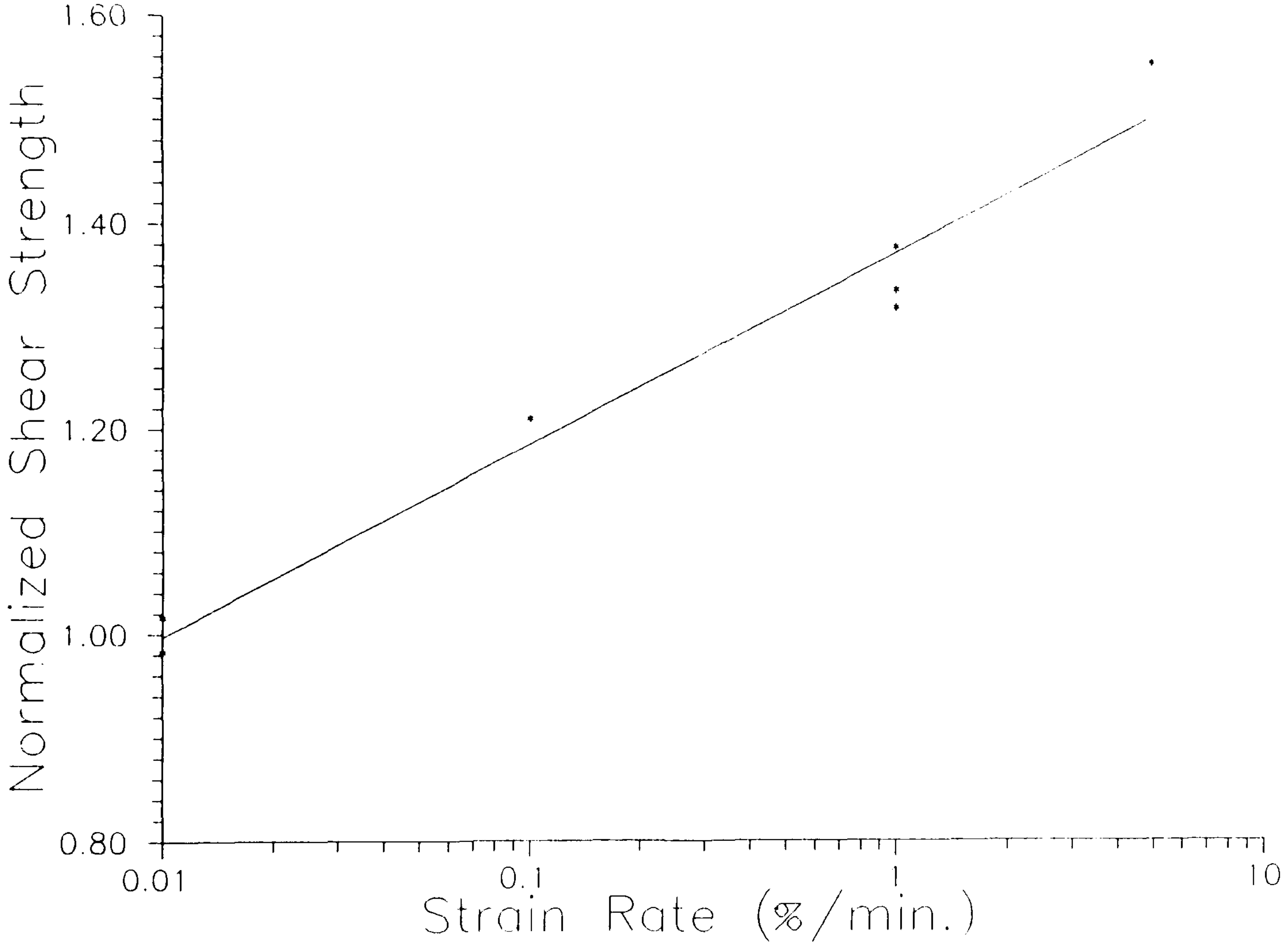

FIG. 2: NORMALIZED SHEAR STRENGTH W.R.T. 0.01%/MIN. VS STRAIN RATE FOR KAOLIN-SILICA MIX

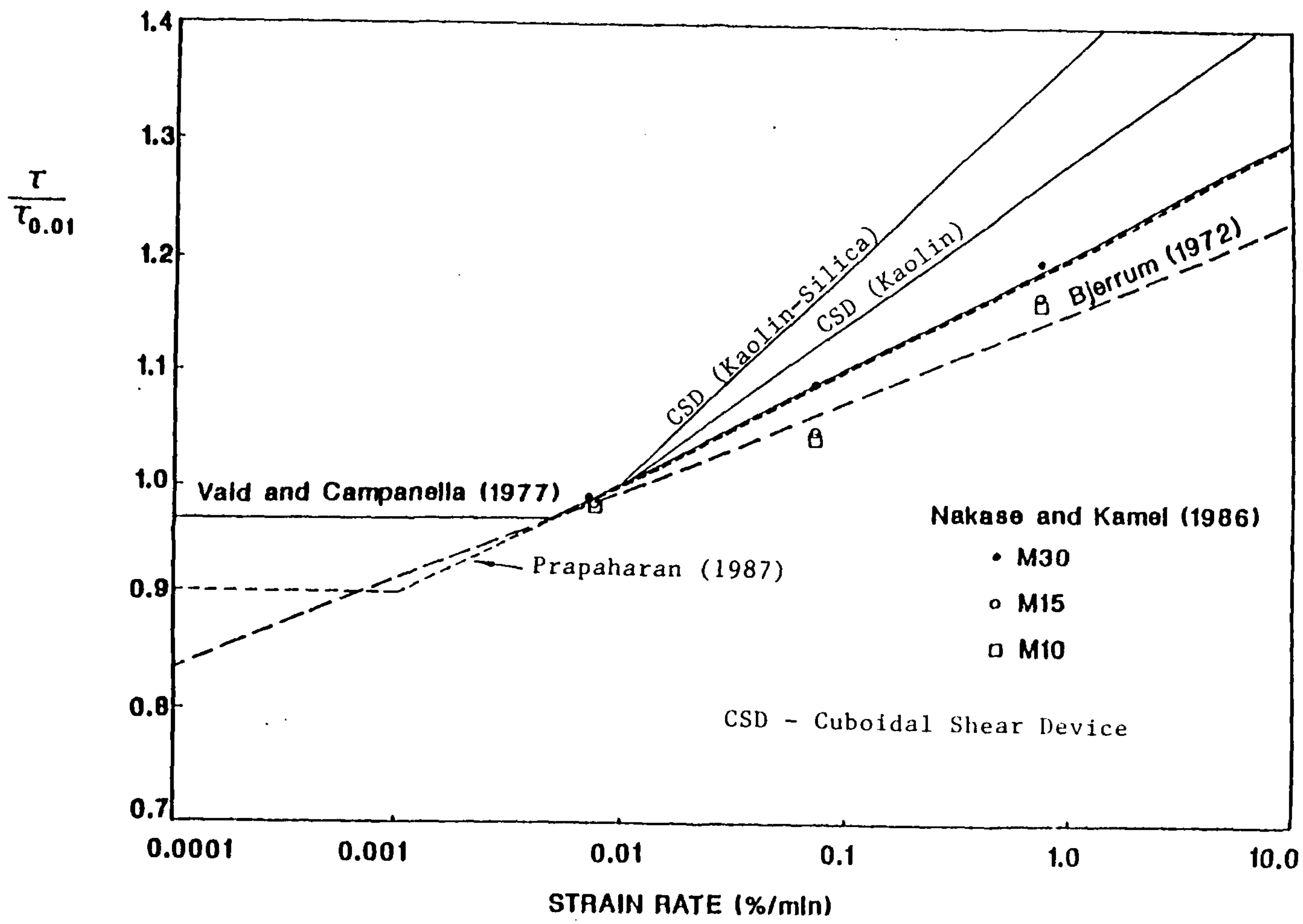

FIG. 3: NORMALIZED SHEAR STRENGTH VS STRAIN RATE

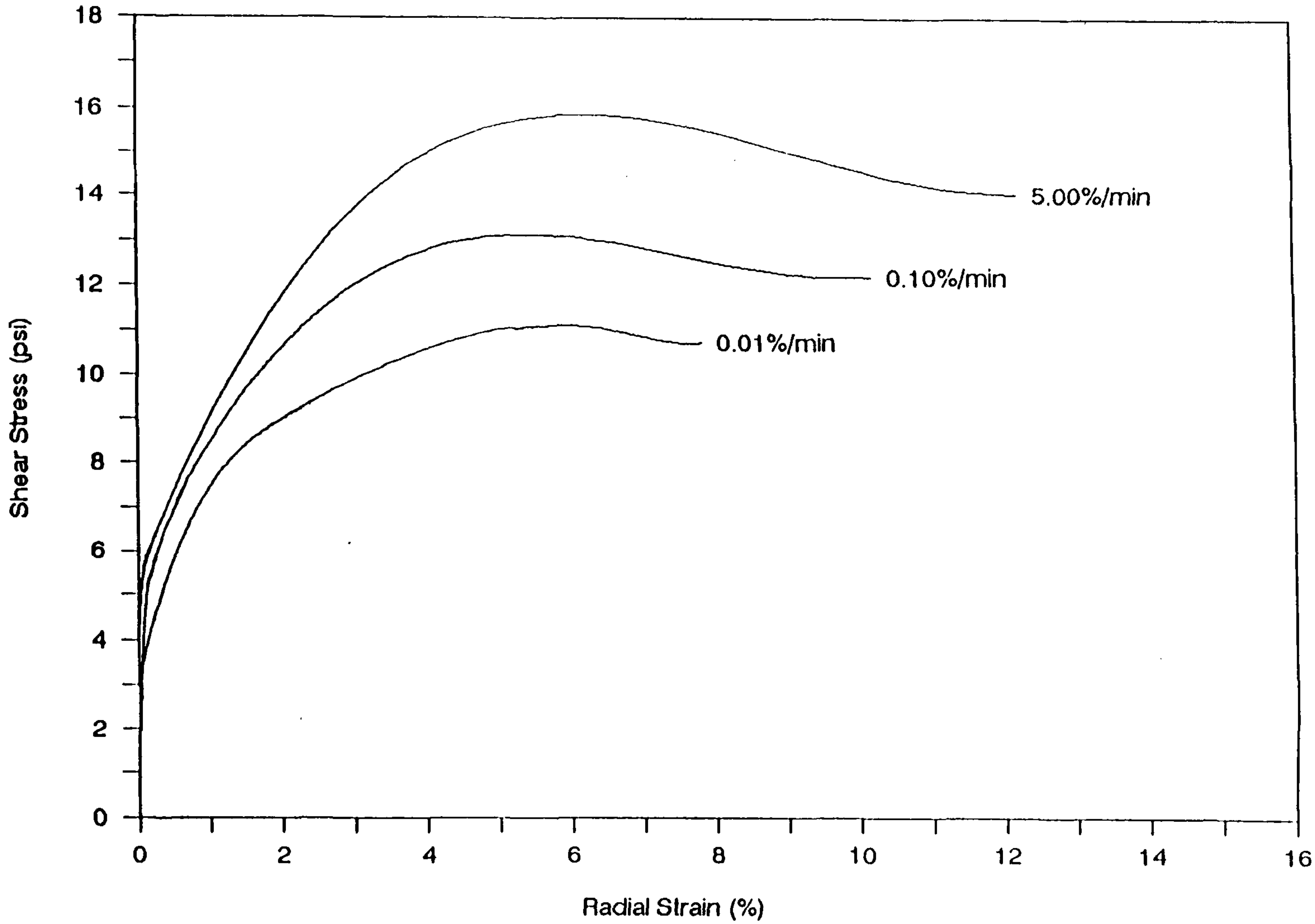

FIG 4 : STRAIN RATE EFFECT ON STRESS-STRAIN CHARACTERISTICS FOR KAOLIN CLAY

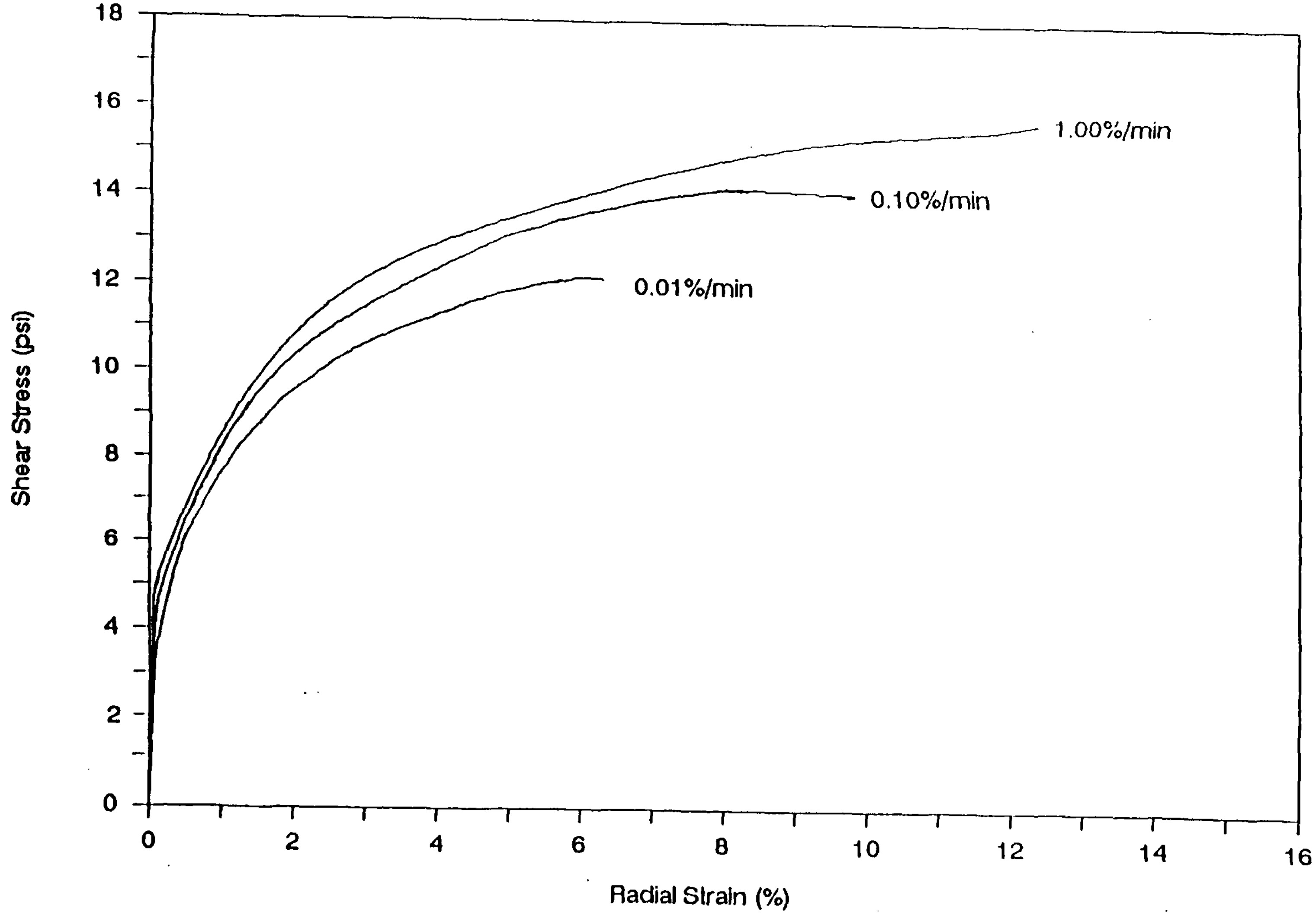

FIG 5 : STRAIN RATE EFFECT ON STRESS-STRAIN CHARACTERISTICS FOR KAOLIN-SILICA MIX